Imaging Techniques for Transverse Profile/Size Monitors

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I. Introduction

II. Beam profiling with YAG:Ce scintillation
   • Scintillator resolution
   • Depth-of-focus issue

III. Optical Transition Radiation (OTR)
   • OTR basics
   • OTR point-spread-function (PSF) aspects
   • Microbunching instability and coherent OTR (COTR)
   • Nonrelativistic beams

IV. Future tests

V. Summary
• The charged-particle beam transverse size and profiles are part of the basic characterizations needed in accelerators to determine beam quality, e.g. transverse emittance.

• A basic beam imaging system includes:
  – conversion mechanism (scintillator, optical or x-ray synchrotron radiation (OSR or XSR), Cherenkov radiation (CR), optical transition radiation (OTR), undulator radiation (UR), and optical diffraction radiation (ODR).
  – optical transport (lenses, mirrors, filters, polarizers).
  – imaging sensor such as CCD, CID, CMOS camera, with or without intensifier and/or cooling
  – video digitizer
  – image processing software
Identify Corrections to Consider

- System related
  - YAG:Ce powder and crystal screen spatial resolution.
  - Camera resolution and depth of focus.
  - OTR polarization effects and OTR point spread function.
  - Camera calibration factor.
  - Finite slit size (if applicable).

- Accelerator / beam related
  - Beta star term in spectrometers.
  - Macropulse blurring effects on energy spread, beam size, and beam divergence in OTR images.
  - Most of the examples will be for electrons.
Observed vs Actual Slit Image Size

- Uncorrelated terms are treated as a quadrature sum to actual image size $Act$ (see Lyons’ textbook $^a$).
  - Observed image size $Obs$
  - YAG screen effects $YAG$
  - Camera resolution $Cam$
  - Finite slit width $Slit$

- In addition there can be macropulse effects and OTR polarization effects.

$$Obs^2 = Act^2 + YAG^2 + Cam^2 + Slit^2$$

and solving for the actual beam size we have,

$$Act = \sqrt{Obs^2 - YAG^2 - Cam^2 - Slit^2}$$

## Converter Screen Properties

<table>
<thead>
<tr>
<th></th>
<th>YAG:Ce (Cerium doped) powder or single crystal</th>
<th>OTR screen, e.g. Al or aluminized Si</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Efficiency</strong></td>
<td>~100x</td>
<td>1x</td>
</tr>
<tr>
<td><strong>Spatial resolution</strong></td>
<td>Volume effect, grain size</td>
<td>EM surface phenomenon</td>
</tr>
<tr>
<td><strong>Spectral content</strong></td>
<td>Narrow band (~20 nm)</td>
<td>Broad band</td>
</tr>
<tr>
<td><strong>Saturation, non-linearities</strong></td>
<td>at high beam intensities</td>
<td>no</td>
</tr>
<tr>
<td><strong>Response time</strong></td>
<td>~50 – 100 nsec</td>
<td>~10 fsec (skin depth)</td>
</tr>
<tr>
<td><strong>Screen geometry:</strong></td>
<td>depth of focus, scattering, effective thickness, system simplicity, etc.</td>
<td></td>
</tr>
<tr>
<td>normal / angular (45°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Screen thickness, energy deposition, beam scattering</strong></td>
<td>100 μm range</td>
<td>minimum: 1 μm (fragile!) maximum: some 100 μm</td>
</tr>
<tr>
<td><strong>Light scattering</strong></td>
<td>Halo effects through scintillating volume</td>
<td>None</td>
</tr>
</tbody>
</table>
YAG:Ce Powder Scintillator Screens

- YAG:Ce screens, used at the A0 Photoinjector:
  - The screens have nominally a 5-µm grain size and are coated at 50-µm thickness on various metal substrates.
  - Substrates are Al or SS and 1 mm thick.
  - In the A0PI arrangement the scintillator was on the front surface of the substrate, and oriented at 45° to the beam direction.
  - Powder screens are kindly provided by Klaus Floettmann (DESY).

- Observed Characteristics
  - The response time is about 80 ns FWHM.
  - There have been reports of saturation of the mechanism for incident electron beam areal charge densities ~10 fC/µm².
    - This effect can cause a charge dependence of the observed image size in addition to the low-charge, screen resolution limit.
Fermilab A0 Photo Injector

Beamline and diagnostics support for EEX applications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>MeV</td>
<td>15</td>
</tr>
<tr>
<td>Energy spread</td>
<td>keV</td>
<td>10 – 15</td>
</tr>
<tr>
<td>transverse emittance</td>
<td>mm mrad</td>
<td>2.6±0.3</td>
</tr>
<tr>
<td>Bunch length</td>
<td>ps</td>
<td>3.1±0.3</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>nC</td>
<td>~0.1 – 5</td>
</tr>
</tbody>
</table>

3.9 GHz TM\textsubscript{110} Cavity
### YAG:Ce Powder vs OTR Screen

<table>
<thead>
<tr>
<th></th>
<th># of bunches</th>
<th>X5 linear polarization</th>
<th>Fit σ (pixel)</th>
<th>X Size (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTR</td>
<td>10</td>
<td>none</td>
<td>5.49 ± 0.05</td>
<td>124.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vertical</td>
<td>4.47 ± 0.09</td>
<td>101.0</td>
</tr>
<tr>
<td>YAG:Ce</td>
<td>1</td>
<td>none</td>
<td>5.67 ± 0.05</td>
<td>128.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vertical</td>
<td>5.71 ± 0.04</td>
<td>129.6</td>
</tr>
</tbody>
</table>

- Both screen surfaces at 45° to the beam direction.
- Gaussian fits to the projected beam profiles of 10 images.
- Deduced YAG resolution term (page 6): 80 ± 20 μm
- Other data sets averaged for YAG term: 60 ± 20 μm
Scintillator screen resolution vs. thickness after applying corrections discussed on page 6.

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Identify Corrections to Consider

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  - Camera calibration factor.
  - Finite slit size (if applicable).

- **Accelerator / beam related**
  - Beta star term in spectrometers.
  - Macropulse blurring effects on energy spread, beam size, and beam divergence in OTR images.
  - Most data examples will be for electrons except one hadron case and one heavy-ion case.
Depth-of-Focus Issues

- 1 mm (X5) / 4 mm (X24) spaced slits, 50 μm wide
  - Camera calibration ~30 μm / pixel.
- Depth-of-focus issues in extended field of view for 45° arrangement of the YAG:Ce scintillator screen

![Graphs showing comparison of X5 and X24 beam data with benchtop resolutions vs. depth.](image-url)
MATLAB Emittance Code

- Application tool provides online emittance and C-S parameter calculations to facilitate operations.
• **System related**
  
  – YAG:Ce powder and crystal screen spatial resolution.
  
  – Camera resolution and depth of focus.
  
  – OTR polarization effects and OTR point spread function.
  
  – Camera calibration factor.
  
  – Finite slit size (if applicable).

• **Accelerator / beam related**
  
  – Beta star term in spectrometers.
  
  – Macropulse blurring effects on energy spread, beam size, and beam divergence in OTR images.
Optical Transition Radiation (OTR)

- OTR can be used for beam
  - profile / size
  - position
  - divergence
- Charged particle passing a media boundary (EM dipole).

OTR angular intensity distribution of a single charged particle
• OTR single particle spectral-angular distribution:

\[ \frac{d^2 N_1}{d\omega d\Omega} = \frac{e^2}{\hbar c} \frac{1}{\pi^2 \omega} \frac{1}{(\gamma^{-2} + \theta_x^2 + \theta_y^2)^2} \]

- \( \Omega \) spatial angle
- \( \omega \) angular frequency
- \( N_1 \) # of photons
- \( \Theta_{x,y} \) radiation angle
- \( e, \hbar, c, \pi \) constants

• Coherent spectral-angular distribution from a macropulse

\[ \frac{d^2 N}{d\omega d\Omega} = \left| r_{\perp,//} \right|^2 \frac{d^2 N_1}{d\omega d\Omega} I(k) \zeta(k) \]

- \( N \) # of photons from per unit frequency and solid angle (typ. 1 e -> 0.001 photons)
- \( r \) reflection coefficient
- \( I \) interference function (double foil)
- \( F \) coherence function (can be non-linear)

\( E = 220 \text{ MeV} \)
\( \sigma_{x', y'} = 0.2 \text{ mrad} \)
Coherence Function

\[ \mathcal{Z}(\mathbf{k}) = N + N_B (N_B - 1) |H(\mathbf{k})|^2 \]

Fourier Transform of Charge Form Factors

\[ H(\mathbf{k}) = \frac{\rho(\mathbf{k})}{Q} = g_x(k_x)g_y(k_y)F_z(k_z) \]

Q = total charge of macropulse

Bunching fraction = \( f_B = \frac{N_B}{N} \)

For the broadband microbunching instability, enhancements can occur at visible wavelengths, COTR.

Note: The coherence function reduces to just the number of particles, \( N \), when the number of microbunched particles, \( N_B \) is zero.

From D. Rule and A. Lumpkin, PAC'01
Prototype Imaging Station

- New developed imaging station in collaboration with RadiaBeam, Inc.
• Switchable assemblies to compare options.
  - Still tweaking!

Option 1

**Impedance Screen**

YAG:Ce, plus Al on Si mirror

OTR, normal to beam, plus Al on Si mirror

Option 2

**Impedance Screen**

OTR, 100 µm Al plus Al on Si mirror

OTR foil, 1µm plus 1µm foil at 45°
Test of OTR Normal to Beam

- Optics focused on crystal location:
  - gives superposition of focused OTR and defocused OTR source from mirror.

Single-Gaussian Fit
\[ \sigma_1 = 16.2 \pm 0.2 \text{ pix} \]

Double-Gaussian Fit
\[ \sigma_1 = 9.2 \pm 0.1 \]
\[ \sigma_2 = 28.1 \pm 0.2 \]
At the diffraction limit \( \Delta x \approx \lambda / \Delta \theta \) the image of a point source radiates a ring pattern defined by the OTR point spread function (PSF):

\[
f^2(\theta_m, \gamma, \varsigma) = \left[ \int_0^{\theta_m} \frac{\theta^2}{\theta^2 + \gamma^2} J_1(\varsigma \theta) d\theta \right]^2
\]

- \( \theta_m \) maximum acceptance angle
- \( M = b / a \) magnification factor
- \( R_i \) radius of the lens

Example:
M=1, E=4GeV, \( \lambda = 500\text{nm} \) courtesy C. Liu (BNL)
• 14.3 MeV, M=1, λ=500 nm, θ_{max}=0.010, \sigma=25 \mu m
• This version with convolutions implemented at FNAL.
• 14.3 MeV, M = 1, \( \lambda = 500\text{nm} \), \( \theta_{\text{max}} = 0.010 \), \( \sigma = 10 \& 50 \mu\text{m} \)

Original Sigma = 10 \( \mu\text{m} \)
Total PSF Sigma = 22.59 \( \mu\text{m} \)
HorPol-HorProj PSF Sigma = NA
HorPol-VerProj PSF Sigma = 16.63 \( \mu\text{m} \)

Original Sigma = 50 \( \mu\text{m} \)
Total PSF Sigma = 55.63 \( \mu\text{m} \)
HorPol-HorProj PSF Sigma = 58.49 \( \mu\text{m} \)
HorPol-VerProj PSF Sigma = 53.05 \( \mu\text{m} \)
Polarized Beam Images at XUR

- OTR Perpendicular component has 15% smaller profile.
  - Beam measurements with a vertical stripe, ~50 μm wide.

Total Pol.: Left
Single-Gaussian Fit
σ₁ = 66.8 ± 0.3 μm

Vert. Pol.: Right
Single-Gaussian Fit
σ₁ = 55.1 ± 1.1 μm

12μm effect @ 55 μm
(Cal.: 5.3 μm/pixel)
KEK staff used vertical polarizer and small beam to observe PSF and suggested potential use of structure.

- Use PSF valley for profile measurements at the PSF limit.

\[ f(x) = a + \frac{b}{1 + [c(x - \Delta x)]^\gamma} \left[ 1 - e^{-\frac{(x - \Delta x)^2}{2\sigma^2}} \cos [\pi c(x - \Delta x)] \right] \quad (1) \]

where \(a\), \(b\), \(c\), \(\sigma\), and \(\Delta x\) are free parameters of the fit function, namely: \(a\) is the vertical offset of the distribution with respect to zero which included a constant background; \(b\) is the amplitude of the distribution; \(c\) is the distribution width; \(\sigma\) is the smoothing parameter dominantly defined by the beam size; and \(\Delta x\) is the horizontal offset of the distribution with respect to zero.
• Estimation of OTR/COTR spectral effect for LCLS case.
COTR Mitigation Test at St-5/ANL

- Reduction of COTR effects with 400x40 nm BPF, but need more sensitive camera than 40dB analog CCD to see remaining OTR.

A.H. Lumpkin       BIW12   April 17, 2012
Proton beams for the neutrinos with the main injector (NuMI) target can be imaged in the transport line.

NuMI OTR Data
- OTR just upstream of target
- 9.4E12 120 GeV protons/spill
- 0.12 μm Al on 6 μm Kapton
  - foil at 45 degrees to beam
• Is there sufficient charge crossing the interface so OTR could be detectable? Use $Q^2$ and $\beta^2$ dependencies.
• Can the thin foil survive the areal charge density levels? (Beamline exit windows and stripper foils do).
• 120-GeV protons, up to $10^{13}$ in a batch in 1mm x 1mm spot on aluminized Kapton (7 µm). Screen survived 6 months in beam at Fermilab.
• Look at lobe angle like 80-keV electrons? Or other.
• Use ICCD, cooled CCD, or CMOS cameras to boost sensitivity to low signals.
• Use Forward OTR; with annular mirror? Out of stripper foil?
• What beam intensity levels used at GSI, LHC, RHIC?
Proposed OTR Application to Heavy Ions

- Consider applying technologies and concepts for ions.
- Take advantage of charge state for OTR generation.

For a non-relativistic charge $Q$, traveling with velocity $v$, the spectral energy density of transition radiation is,

$$W(\omega) = 4 \frac{Q^2 \beta^2}{3 \pi c},$$

where $\beta = v/c$ and $c$ is the speed of light.

Ginzburg and Tsyovich,(1984)

More than a “gedanken” experiment!
### Table I. Comparison of various particle beam cases and estimated OTR photons generated (Preliminary).

<table>
<thead>
<tr>
<th>Part.</th>
<th>E(MeV)</th>
<th>Q</th>
<th>β</th>
<th>γ</th>
<th>Y(ph/e)</th>
<th>N</th>
<th>Mult.</th>
<th>Photon #</th>
<th>CCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>e^-</td>
<td>.080</td>
<td>1</td>
<td>0.65</td>
<td>1.15</td>
<td>2x10^{-6}</td>
<td>4x10^{11}</td>
<td>1</td>
<td>7x10^5</td>
<td>Int.</td>
</tr>
<tr>
<td>e^-</td>
<td>150</td>
<td>1</td>
<td>0.99</td>
<td>300</td>
<td>10^{-3}</td>
<td>6x10^9</td>
<td>-</td>
<td>6x10^6</td>
<td>CCD</td>
</tr>
<tr>
<td>p^+</td>
<td>120x10^3</td>
<td>1</td>
<td>0.99</td>
<td>129</td>
<td>10^{-3}</td>
<td>10^{11}</td>
<td>-</td>
<td>10^8</td>
<td>CID</td>
</tr>
</tbody>
</table>

**MeV/u**

<table>
<thead>
<tr>
<th>Part.</th>
<th>E(MeV)</th>
<th>Q</th>
<th>β</th>
<th>γ</th>
<th>Y(ph/e)</th>
<th>N</th>
<th>Mult.</th>
<th>Photon #</th>
<th>CCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>11.4</td>
<td>10</td>
<td>0.15</td>
<td>1.01</td>
<td>10^{-6}</td>
<td>10^{10}</td>
<td>5.3</td>
<td>5x10^4</td>
<td>*Int.</td>
</tr>
<tr>
<td>U</td>
<td>11.4</td>
<td>28</td>
<td>0.15</td>
<td>1.01</td>
<td>10^{-6}</td>
<td>10^{11}</td>
<td>42</td>
<td>4x10^6</td>
<td>*Int.</td>
</tr>
<tr>
<td>U</td>
<td>300</td>
<td>73</td>
<td>0.65</td>
<td>1.21</td>
<td>10^{-6}</td>
<td>10^9</td>
<td>5329</td>
<td>5x10^6</td>
<td>*Int.</td>
</tr>
</tbody>
</table>

*Use intensifier for gain and the gating feature. More discussions later today. Also the ion intensity increases projected for FAIR look even better for photon numbers. The Multiplier (Mult.) column is the scaling with Q^2β^2.*
Experimental Setup at GSI

Experimental setup consists of an OTR target ladder (6 targets on one ladder) and image-intensified CCD camera system (ICCD) from PROXITRONIC.

- the exact ICCD gating feature (down to 10 μs) was used to select preferentially the prompt OTR signal versus any background sources in the scene.

*GSI slides provided by B. Walasek-Hohne

For future investigations we reduced beam current!
Q^2 dependence

- Figure compares raw data of beam distributions for both charge states, but same ion number of \( \sim 7 \cdot 10^8 \). The ratio of the integral ICCD intensities roughly supports the predicted Q^2 dependence: \( 3.3/0.49 \sim 73^2/28^2 \) for chosen ROI.

*GSI slide provided by B. Walasek-Hohne*
Light yield versus particles per pulse

• OTR light yield scales linearly with particle number

*GSI slide provided by B. Walasek-Hohne
Proposed FACET test at 23 GeV

- New parameter space for OTR/ODR tests provided at FACET.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>APS</th>
<th>CEBAF</th>
<th>ILC</th>
<th>FACET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>7</td>
<td>1- 5</td>
<td>5,15,250</td>
<td>23</td>
</tr>
<tr>
<td>X Beam size (μm)</td>
<td>1300</td>
<td>80-100</td>
<td>300,150,30</td>
<td>10</td>
</tr>
<tr>
<td>Y Beam size (μm)</td>
<td>200</td>
<td>80-100</td>
<td>15,8,2</td>
<td>10</td>
</tr>
<tr>
<td>Current (nA)</td>
<td>6</td>
<td>100,000</td>
<td>50,000</td>
<td>30</td>
</tr>
<tr>
<td>Charge/ 33 ms (nC)</td>
<td>3</td>
<td>3,000</td>
<td>10,000</td>
<td>3</td>
</tr>
</tbody>
</table>

- FACET parameters closer to ILC parameters.
• Injector being installed with First beam expected in 2012.

40-MeV Injector

- Booster cavity 2 (from DESY and Saclay) installed in NML
- First cryomodule (from DESY) installed at NML

Courtesy of M. Church
Summary

• Scintillator resolution terms should be characterized,
  - Use normal incidence of beam as preferred geometry to
    minimize depth-of-focus issues in beam images.

• OTR polarization effects need to be elucidated
  - Plan to optimize OTR PSF and optical resolution.
  - Plan to use linear polarizers with OTR imaging for the
    perpendicular profile components at ASTA.

• Mitigate microbunching instability effects
  for profiling of bright beams.
  - Plan to use 400x40 nm band pass filters and LYSO:Ce crystals
    after bunch compression at ASTA to suppress expected
    diagnostics complications due to COTR.

• New paradigm for heavy-ion beam imaging with OTR.
• The future remains bright for imaging techniques.
ODR is a Potential Nonintercepting Diagnostic for GeV Lepton Beams and TeV Hadron Beams

- At left, schematic of ODR generated from two vertical planes (based on Fig. 1 of Fiorito and Rule, NIM B173, 67 (2001). We started with a single plane.
- At right, calculation of the ODR light generated by a 7-GeV electron beam for $d=1.25$ mm in the optical near field based on a model (Rule and Lumpkin).

\[
a/2 = d\gamma\lambda/2\pi
\]
7-GeV Test at APS

Lumpkin et al., PRST-AB (Feb. 2007)
ODR model: FACET Case

- Vertical polarization component, \( \lambda = 800 \text{ nm} \),\n  \( \text{IP} = 100, 50 \mu \text{m} \). Curves for 10, 20, 35, 50, 100 \( \mu \text{m} \).

- Better sensitivity predicted for \( \text{IP} = 50 \mu \text{m} \) (\( \approx 5 \sigma_r \))
Further ODR Studies Proposed

- Path to test near-field imaging on 10-µm size at 23 GeV.